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# Conference Summary: Three-Dimensional Explosions

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## 1.1 Introduction

This conference was packed with interesting and relevant developments regarding the three-dimensional nature of both thermonuclear and core-collapse supernovae. Before summarizing those presentations, I would like to summarize some of the developments regarding rotation and magnetic fields that were on my mind during the conference.

## 1.2 Dynamo Theory and Saturation Fields

There has been a major breakthrough in the conceptual understanding of astrophysical dynamos in the last few years. In traditional mean field dynamo theory, the turbulent velocity field that drives the “alpha” portion of the  $\alpha - \Omega$  dynamo was specified and held fixed. A weakness of the original theory was that the turbulent velocity field cannot be constant. The buildup of small scale magnetic field tends to inhibit turbulence, cutting off the dynamo process for both small and large scale fields. Since the small scale field tended to grow faster than the large scale field, it appeared that the growth of the large scale field would be suppressed (Kulsrud & Anderson 1992; Gruzinov & Diamond 1994). In these theories, the magnetic field energy cascades to smaller length scales where it is ultimately dissipated at the resistive scale. Large scale fields tend to build up slowly, if at all.

The solution to this problem has been the recognition (Blackman & Field 2000; Vishniac & Cho 2001; Field & Blackman 2002; Blackman & Brandenburg, 2002; Blackman & Field 2002; Kleeorin et al. 2002) that the magnetic helicity,  $\mathbf{H} = \mathbf{A} \cdot \mathbf{B}$  is conserved in ideal MHD and that this conservation had not been treated explicitly in mean field dynamo theory. Incorporation of this principle leads to an “inverse cascade” of helical field energy to large scales that is simultaneous with the cascade of helical field energy from the driving scale to the dissipation scale. Basically, the large scale helical field and inverse cascade must exist with opposite magnetic helicity to that of the field cascading to small scale. The result (Blackman & Brandenburg 2002) is the rapid growth of large scale field in a kinematic phase (prior to significant back-reaction) to a strength where the field on both large and small scales is nearly

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in equipartition with the turbulent energy density. At that point, the back reaction sets in and there tends to be a slower growth to saturation at field strengths that can actually somewhat exceed the turbulent energy density. It may be that the early, fast, kinematic growth is the only phase that is important for astrophysical dynamos, especially in situations that have open boundaries so that field can escape (Brandenburg, Blackman & Sarson 2003; Blackman & Tan 2003) and that are very dynamic. The collapse ambience is clearly one of those situations.

Another possibly important insight is that the rapid kinematic phase can lead to magnetic helicity currents (Vishniac & Cho 2001). It is possible that these magnetic helicity currents can transport power out of the system in twisting, propagating magnetic fields. This is clearly reminiscent of jets or winds, but the physics is rather different than any that has been previously explored in driving jets or winds. This physics needs to be explored in the context of supernovae and gamma-ray bursts.

This new work on dynamo theory has not changed one basic aspect and that is the level of the saturation fields. It remains true that the saturation fields will be of order  $v_a \sim \lambda\Omega$  or  $B^2 \sim 4\pi\rho\lambda^2\Omega^2$  where the characteristic wavelength,  $\lambda \lesssim r$ , for quasi-spherical situations. For a proto-neutron star this yields a field of order  $10^{15}$  to  $10^{16}$  G. For collapse to form a black hole, the velocities will be Keplerian and the associated, dynamo-driven, predominantly toroidal field will have a strength of order  $B \sim 10^{16} \text{G} \rho_{10}^{1/2}$  assuming motion, including the Alfvén speed, near the speed of light near the Schwarzschild radius and a characteristic density of order  $10^{10} \text{g cm}^{-3}$  (MacFadyen & Woosley 1999). Fields this large could affect both the dynamics and the microphysics in the black hole-formation problem. Because of the nearly Keplerian motion in the black hole case, the fields generated will be much closer to pressure equipartition than in the neutron star case, and hence, perhaps, even more likely to have a direct dynamical effect. The associated MHD power in the black hole case would be roughly  $10^{52} - 10^{53} \text{erg s}^{-1}$ .

### 1.3 Possible Effects of Large Magnetic Fields

#### A. Equation of State

Fields of order  $10^{15}$  to  $10^{16}$  G are far above the QED limit,  $B_{QED} = 4 \times 10^{13}$  G, so quantum effects may become important. The calculations of Akiyama et al. (2003) predict regions  $\sim 10^6$  to  $10^7$  cm where the electron Fermi energy is less than the first Landau level after about 100 ms (see the contribution in these proceedings by Akiyama et al.). In such conditions, electron motions will be quantized, with the electron component of the pressure being strongly anisotropic. This pressure anisotropy is likely to be balanced by the  $\mathbf{j} \times \mathbf{B}$  force of induced magnetization (Blandford & Hernquist 1982), but in the absence of such isotropy, pressure anisotropy of order  $10^{-4}$  and hence velocity anisotropy of order  $10^{-2}$  might be induced. The electron pressure will be reduced compared to calculations that ignore quantization, but it is not clear that will make a significant difference to the dynamics.

For  $B > B_{QED}$ , the electrons can only flow along the field lines, that is  $\mathbf{j} \parallel \mathbf{B}$ . On the other hand, classic MHD includes currents only implicitly and assumes that the current is always normal to the field,  $\mathbf{j} \perp \mathbf{B}$ . The result is a manifest contradiction, as

pointed out to me by Dave Meier. The resolution to this might be non-local currents, ion currents (which would require flows of only  $10^{-6} \text{ cm s}^{-1}$ ), or most interestingly, but unlikely, a field that saturates at the QED limit. These issues are worth more thought.

#### B. Neutrino Transport

Fields of order  $10^{15}$  to  $10^{16}$  G that will characterize both neutron star and black hole formation may affect neutrino transport. With a large magnetic field, direct  $\nu - \gamma$  interaction is possible mediated by W and Z bosons. This would allow neutrino Cerenkov radiation,  $\nu \rightarrow \nu + \gamma$ , and would enhance plasmon decay,  $\gamma \rightarrow \nu + \nu$  (Konar 1997).

In addition, processes like  $\nu \rightarrow \nu + e^+ + e^-$  would no longer be kinematically forbidden. In that case, closed magnetic flux loops can trap pairs. The energy in pairs would grow exponentially to the point where annihilation cooling would balance pair creation. Thompson & Duncan (1993) estimated that an energy as much as  $E_{\text{pair}} \sim 10^{50}$  erg could be trapped in this way. This is not enough energy to cause a robust explosion, but it is enough energy to drive the dynamics of core collapse in a substantially different way, perhaps by inducing anisotropic flow if the flux loops are themselves distributed anisotropically.

With substantial magnetic fields, the cross section for inverse beta decay,  $\nu_e + n \rightarrow p + e^-$ , would become dependent on neutrino momentum, especially for asymmetric field distributions, which would be the norm (Lai & Qian 1998; Bhattacharya & Pal 2003; Ando 2003).

All these processes and more should be considered quantitatively in core collapse to form neutron stars and black holes.

### 1.4 Core Collapse MHD and Jet Formation

#### A. Magnetic Helicity Currents

It is not at all proven that the large magnetic fields expected in core collapse generate jets, but there are a number of clues pointing in that direction. For the more traditional situation in which collapse leads to the formation of a neutron star, the premise is that there is a rapid formation of a strong magnetic field with  $B \sim 100 B_{\text{QED}} \ll (4\pi P)^{1/2}$ , that is much above the QED limit, but less than equipartition with the ambient pressure. This field is expected to be primarily toroidal (simulations give  $\sim 80\%$ ; Hawley Gammie & Balbus 1996), but turbulent, with a maximum around the proto-neutron star surface, a location well within the standing shock. The expected MHD power,  $\sim 10^{52} \text{ erg s}^{-1}$ , would be delivered in some form beneath that shock and could help to reinvigorate it, or to provide entirely unique, jet-like dynamics in which the shock no longer played a key role. In this highly magnetized environment, there will be hoop stresses, gradients in magnetic pressure and perhaps in the electron pressure. These anisotropic components will be weak compared to the total pressure, but they will be non-radial and anisotropic.

As an example of the possibly relevant physics, Vishniac & Cho (2001) argue that

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along with conservation of magnetic helicity,  $\mathbf{H} = \mathbf{A} \cdot \mathbf{B}$ , and the inverse cascade of magnetic field energy to large scales, one will get a current of magnetic helicity that can be crudely represented by

$$J_H \sim B^2 \lambda v, \quad (1.1)$$

where the characteristic length,  $\lambda$ , might be comparable to a pressure scale height,  $\ell_P = (d \ln P / dr)^{-1}$ , and  $v \sim v_a \sim \ell_P \Omega$ . The energy flux associated with this magnetic helicity current is  $J_H / \lambda \sim B^2 v_a$ , and so with  $B^2 \sim \rho \ell_P^2 \Omega^2$  the associated power is:

$$L = r^2 B^2 v_a \sim B^2 r^2 \ell_P \Omega \sim \rho r^5 \Omega^3 \left( \frac{\ell_P}{r} \right)^3. \quad (1.2)$$

Note that the next-to-last expression on the RHS is essentially just the characteristic Blandford-Payne luminosity (Blandford & Payne 1982); however, in this case the field is not externally given, but provided by the dynamo process so that the final expression on the RHS is given entirely in terms of local, internal quantities. The implication is that this amount of power is available in an axial, helical field without twisting an external field. Again, while this analysis has superficial resemblance to other jet mechanisms, it involves rather different physics and is self-contained. Whether this truly provides a jet remains to be seen. A first example of driving a polar flow with the MRI is given by Hawley & Balbus (2002).

Note that this process of creating a large scale field with an MRI-driven dynamo with its promise of naturally driving axial, helical flows does not require an equipartition field. As pointed out by Wheeler et al. (2002), the field does not have to have equipartition strength and hence to be directly dynamically important in order to be critical to the process of core collapse. The field only has to be significantly strong to catalyze the conversion of the free energy of differential rotation of the neutron star into jet energy. As long as this catalytic function is operative, the rotational energy should be pumped into axial flow energy until there is no more differential rotation. For the case of stellar collapse, this would seem to imply that, given enough rotational energy in the neutron star, this machine will work until there is a successful explosion. Even if the core collapses directly into a black hole, or does so after some fall-back delay, the basic physics outlined here, including magnetic helicity currents and their associated power should also pertain to black hole formation.

#### B. Poleward Slip Instability

Another interesting bit of physics that may pertain to core collapse is the poleward slip instability. This is analogous to wrapping a rubber band around the equator of a ball and then sliding it upward. For the case of a magnetized plasma, a toroidal field is absolutely unstable to this effect in the absence of rotation (Spruit & Ballegoijen 1982). The case with differential rotation has been considered by, among others, Chanmugam (1979). In that case the axisymmetric ( $m = 0$ ) mode still appears to be unstable, but this case is a bit tricky because the absence of a sufficient condition for stability as derived by Chanmugam does not necessarily imply a necessary and sufficient condition for instability. The interesting behavior, in any case, is not merely

the linear instability, but the non-linear dynamics. This does not seem to have been explored at all in the literature.

As a crude way of examining this, let us assume that the pressure gradient balances gravity to first order and look at the acceleration resulting from the hoop stress and centrifugal potential, assuming conservation of angular momentum of the matter associated with a flux tube. The result is

$$a \sim \frac{v_a^2}{r} - \frac{R^4 \Omega_{eq}^2}{r^3}, \quad (1.3)$$

where  $r$  is the cylindrical radius,  $R$  the value on the equator, and  $\Omega_{eq}$  the value of the angular velocity on the equator. For the case of interest, the saturation field condition is that  $v_a \sim R\Omega_{eq}$ , so that these terms nearly cancel on the equator. This is a caution, at least, that care must be taken to take all the forces into account self-consistently. The issue of what happens as the field starts to slip toward the pole seems to depend on the behavior of the Alfvén velocity, and hence the magnetic field and entrained density, as the flux tube moves.

Note that the poleward slip instability, whatever its ultimate non-linear behavior, should not depend on whether the field is continuously connected around the body (literally like a rubber band) or whether it is turbulent and discontinuous. This is because, for instance, the hoop stress is a local property of a field with a mean radius of curvature. Williams (2003 and this conference) has argued that even a tangled field with  $\langle B \rangle \sim 0$ , but  $\langle B^2 \rangle^{1/2} \neq 0$ , will act like a viscoelastic fluid (see also Ogilvie 2001) and, in particular, exert a hoop stress.

The conjecture is that the ultimate non-linear behavior is for the field to accumulate near the pole where it reaches approximate equipartition,  $B \sim (8\pi P)^{1/2}$ , and hence becomes dynamically significant. Again, this suggests activity at the pole that is reminiscent of a jet. Yet again, this remains to be seen.

One interesting aspect of the poleward slip instability is that it would seem to pertain directly to neutron stars that have a strong density gradient at the surface, essentially a hard surface, but it should *not* work for black holes, where there is no surface to support the poleward slip. Whether or not this makes any difference in the jet formation in neutron stars versus black holes is an interesting question.

## 1.5 Summary of Contributions

### 1.5.1 *Asymmetry Rules*

The conference began with excellent summaries of the new and growing sample of supernova spectropolarimetry by Lifan Wang and Alex Filippenko. It is this data that has driven the new conviction that core collapse supernovae are essentially universally asymmetric and that the asymmetry is driven by the engine of core collapse itself. With this new conviction, disparate data on otherwise isolated events like the Crab nebula with its pulsar and jet, Cas A, and SN 1987A, begin to make sense in a large picture of fundamentally asymmetric supernovae. Roger Chevalier discussed our evolving knowledge of supernova remnants and pulsar wind nebulae. Rob Fesen described observations on the morphology of supernovae remnants, especially Cas A. Bob Kirshner summarized the imaging spectroscopy on SN 1987A. Doug Swartz

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described the new data on supernova remnants available from the Chandra Observatory. Vikram Dwarkadas showed that his multidimensional simulations of supernova ejecta colliding with previously expelled wind material are rife with Rayleigh-Taylor instabilities and look remarkably like the observations.

One of the lessons that comes through from this work is that neither Type Ia nor the zoo of core collapse supernovae are spherically symmetric. Peter Höflich and the fully-represented Oklahoma mafia – David Branch, R. C. Thomas, Dan Kasen, and Eric Lenz, with Eddie Baron kibbutzing from the audience – outlined the various ways in which polarization could be induced in supernova spectra. Among these are: an intrinsically asymmetric shape, blocking of part of the photosphere by some off-center distribution of matter, and an off-center energy source. All of these may contribute in various supernovae or even for a single supernova, depending on circumstances.

### *1.5.2 Type Ia*

As mentioned in my introduction, one of the goals of the study of Type Ia supernova research for decades has been to obtain direct observational evidence that Type Ia arise in binary systems, as widely accepted on circumstantial grounds. This conference may have revealed some of the first evidence in this direction. Lifan Wang, Peter Höflich, and Dan Kasen discussed the observations and interpretations of polarization data from Type Ia supernovae, particularly the “normal” event SN 2001el that shows remarkable departure from symmetry in the form of a highly polarized high-velocity component to the Ca II IR triplet. After the conference, Gerardy et al. (2003) submitted a paper arguing that a similar high-velocity Ca feature in SN 2003du might arise in a hydrogen-rich circumstellar medium. The data have not yet revealed definite proof, but tantalizing suggestions that the asymmetry may be connected to a disk or binary companion, the existence of which would be proof that a binary system was needed.

Mario Hamuy added a dramatic new development in this area with his discussion of SN 2002ic, an event that shows familiar Type Ia features, but also strong hydrogen emission lines similar to those from Type II<sub>n</sub>. A substantial amount of hydrogen, of order a solar mass, must be involved. After the conference, Wang et al. (2003) submitted a paper based on VLT spectropolarimetry observations that showed that the hydrogen envelope is substantially polarized and probably arrayed in a large, dense, clumpy disk-like way. SN 2002ic is very similar both near maximum light and 200 days later to SN 1997cy and SN 1999E, both classified as Type II<sub>n</sub>. This raises the issue of whether or not at least some of these events previously classified as SN II<sub>n</sub> are hydrogen-surrounded Type Ia. These events are rather rare, so it cannot be true that all Type Ia erupt in this configuration, but it is also clear that Hamuy has provided us with a stimulating new avenue of exploration of the nature of Type Ia and their binary configuration.

As a complement to this, Don Winget described the work that he and his group are doing with asteroseismology to probe the inner composition of white dwarfs. Sumner Starrfield and S.C. Yoon gave very thought-provoking summaries of their work that gives new insights into the possible configurations of white dwarf accretion

and growth that could lead to Type Ia explosions. Jim Truran and Andy Howell both provided insights into how the diversity of Type Ia supernovae may arise.

There has been amazing progress on understanding and simulating the combustion physics associated with Type Ia thermonuclear explosions, as summarized by Alexei Khokhlov, Elaine Oran, Vadim Gamezo, Eli Livne, and Peter Höflich. In particular Gamezo illustrated the state of the art with a three-dimensional simulation of a detonation that starts deep in the fingers of unburned carbon and oxygen that survive at the end of the phase of subsonic, turbulent, deflagration. Fundamental understanding of the deflagration/detonation transition in this “unconfined” problem may be just around the corner.

We also had summaries of the dramatic application of Type Ia supernovae to cosmology and the prospects for probing the “dark energy” from Brian Schmidt and Saul Perlmutter. The astounding discovery of the acceleration of the Universe did not depend on any deep understanding of the physics of the explosion, nor on the evidence for asymmetry being revealed by spectropolarimetry. As we try to measure the effective acceleration as a function of space and time, effectively the equation of state of the dark energy, systematic effects must be mastered at an unprecedented level of precision. This will require a greater physical understanding and an understanding of the origin of the asymmetries that may give a dependence of the luminosity on the angle of observation. If all Type Ia are basically alike, then such angle-dependent effects will average out in a large sample, but if, for instance, the cause of the asymmetry varies with redshift because the underlying cause of the asymmetry does, then great care will be required to make the appropriate analysis of the high-redshift observations.

### 1.5.3 *Core Collapse*

To emphasize, the lesson that emerges strongly from recent studies of the polarization of supernovae and related issues is that core collapse supernovae are always asymmetric, and frequently, but not universally, bi-polar. I must emphasize that this is a hard won conclusion, with heroic observational work by Lifan Wang and by Doug Leonard, Alex Filippenko and their colleagues.

In terms of giving credit, Stirling Colgate revealed the true father of modern supernova research: Scratchy Serapkin. Anatoly Serapkin was the head of the Soviet delegation to the Geneva talks aimed at the Limited Test Ban Treaty to abandon space, atmospheric, and underwater nuclear talks in 1963. Colgate was one of the representatives on the U.S. side with the self-appointed goal of convincing both sides that we needed to understand the astrophysical “background” to avoid confusing a natural event with a bomb test. The yet-to-be famous Vela satellites played a role in these discussions. Colgate said supernovae might be confused with a test. Scratchy, not a scientist himself, fixed him with a steely glare and inquired, “Who knows how supernovae work?” Colgate realized what thin ground he, and the U.S. delegation, were on, returned to Livermore and made the case to Edward Teller that understanding supernovae must become a primary goal of the lab. The rest is history.

At this conference, new perspectives on the mechanisms of core collapse, neutrino transport, rotation, and magnetic fields were given by Stirling Colgate, Adam Burrows, Thierry Foglizzo, Dave Meier, Dong Lai, and Peter Williams. The impact

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of asymmetries on the dynamics and on the question of neutron star versus black hole formation were also discussed. Issues of nucleosynthesis were discussed by John Cowan, Keichi Maeda, and Raph Hix.

Mario Hamuy also spoke about the large range in apparent kinetic energy of the explosions of Type II supernovae. He raised the question of whether or not the distribution of energy is a continuum, or is more complex, implying, perhaps, different physical processes. An example would be neutron star versus black hole formation. These questions must also be posed for Type Ic supernovae. We need to determine if the events labeled “hypernovae” by Maeda and his collaborators are truly special, or part of a continuum. Given the evidence for strong asymmetries, there will be line-of-sight effects early on. Asymmetric flows are also apt to alter the systematics of gamma-ray deposition in later phases, and hence the luminosity and slope of the radioactive tail. Alejandro Clocchiatti reported some old, but still quite relevant, data on Type Ic events that may help to resolve such issues.

Norbert Langer argued that the variations in single star and binary evolution make it unlikely that all massive stars will undergo the same rotational history. Thus, it is improbable to have all iron cores evolve with the same rapid rotation prior to collapse as may be required for MHD jet models of supernovae and of GRBs. Rotation remains a key parameter in stellar evolution studies and, as for collapse dynamics, it is unlikely that rotation will be present in the absence of magnetic fields. Both rotation and magnetic fields must be included self-consistently from the proto-stellar phase to collapse before we really understand this issue. It may not be appropriate, for instance, to evolve a model star a considerable amount and then add the effects of magnetic viscosity once some amount of shear has developed.

### 1.6 **Gamma-Ray Bursts**

We ended the conference with a stimulating session on GRBs and their possible connection to supernovae. Tom Matheson brought the exciting observations by his team of supernova SN 2003dh associated with GRB 030329. This supernova apparently closely resembled SN 1998bw despite the fact that GRB 030329 was a “normal,” if exceptionally close, GRB and that GRB 980425, if associated with SN 1998bw, was rather odd. Given the likelihood of asymmetries and large variations in energy, it is not at all clear why these two supernovae should be so similar.

Don Lamb summarized work on the X-ray rich bursts discovered by HETE, concluding that the gamma-ray component might be more collimated than previously thought and hence that the rate of explosion of GRBs might rival that of SN Ic. Edo Berger, on the other hand, presented radio data on SN Ic that apparently showed that rather few Type Ic could be associated with GRBs. Alin Panaitescu outlined his work with Pawan Kumar that was more consistent with the “standard” value of collimation, but consistent for some bursts with magnetic fields that were quite large in the early, reverse shock phase, and that then decayed with time. Brad Schaefer illustrated how use of the variability/luminosity and spectral lag/luminosity relations are both self-consistent and potentially useful tools to provide distance estimates to GRBs and hence to use GRBs as independent cosmological probes.



## 1.7 Conclusions and Charge

With SN 2003dh, we have incontrovertible evidence that at least some GRBs are associated with spectrally identifiable supernova explosions. This still leaves open a raft of fascinating questions. What is the machine of the explosion? My bet is that it involves rotation and magnetic fields. With the results of Panaitescu and Kumar and of Coburn & Boggs (2003), there are new suggestions that the magnetic field may not just be required to produce synchrotron radiation, but may be dynamically important in producing the burst. If (long) GRBs are routinely associated with the collapse of massive stars, how does the burst and associated magnetic field get out of the star? Another important question, touched on above, is what fraction of Type Ic supernovae make GRBs? If GRBs come from massive stars, why do we not see evidence for winds and shells, dense circumstellar media, in every burst? Must all (again long) GRBs be associated with the formation of black holes, or can some be associated with neutron stars? Do we expect the distribution of rotation rates of stars to vary over the history of the Universe, and if so, should there be some impact on the rate of production of GRBs with redshift?

These are important questions, but there are fundamental issues lying at the core of all of them. That leads to my charge to attendees of the meeting and to readers of these proceedings. *Go thee forth and think about rotation and magnetic fields!*

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